

Inflows in massive star formation regions

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ABSTRACT

How high-mass stars form remains unclear currently. Calculation suggests that the radiation pressure of a forming star can halt spherical infall, preventing its further growth when it reaches $10 M_{\odot}$. Two major theoretical models on the further growth of stellar mass were proposed. One model suggests the mergence of less massive stellar objects, and the other is still through accretion but with the help of disk. Inflow motions are the key evidence of how forming stars further gain mass to build up massive stars. Recent development in technology has boosted the search of inflow motion. A number of high-mass collapse candidates were obtained with single dish observations, mostly showed blue profile. The infalling signatures seem to be more common in regions with developed radiation pressure than in younger cores, which opposes the theoretical prediction and is also very different from that of low mass star formation. Interferometer studies so far confirm such tendency with more obvious blue profile or inverse P Cygni profile. Results seem to favor the accretion model. However, the evolution tendency of the infall motion in massive star forming cores needs to be further explored. Direct evidence for monolithic or competitive collapse processes is still lack. ALMA will enable us to probe more detail of gravity process.

Subject headings: stars: formation—stars: pre-main sequence—ISM: kinematics and dynamics

1. Introduction

Gravitational collapse is an essential process for star formation. However, when the forming stellar object reaches $10 M_{\odot}$, the strong radiation pressure can halt material falling (Wolfire & Cassinelli 1987). A new model that more massive stars can be formed through coalescence of less massive stellar objects was suggested (Bonnell et al. 1998). The accretion model was also improved (Yorke & Sonnhalter 2002; Jijina & Adams 1996). Observational evidences of material inward motions in massive star formation regions are critical to test these models. Nevertheless it is more difficult to seek material infalling in massive star formation regions than in low mass ones because of their complex environment, large distance and quick evolution. The interactions between environment of massive young stellar objects and their feedback bring additional difficulties for the identification of the gas infall motion. The development of millimeter and sub-millimeter equipments made such probing as feasible. In the recent decade not only a number of searches for the gravitational evidence in high mass star formation regions were carried out by single dishes, but typical sources were also examined with interferometers. These have greatly deepened our understanding of massive star formation. Since some basic questions still remain, more observations are needed in the future.

2. Surveys of inflow motions in massive star formation regions

Ten years after the blue profile detected in the low mass core of B335 (Zhou et al. 1993) it was found in a spectroscopic survey toward 28 massive star formation cores associated with H_2O masers (Wu & Evans 2003). With CSO and IRAM, HCN (3-2), CS (5-4), (3-2), (2-1), and $H^{13}CN$ (3-2) were used as optically thick and thin lines, blue profiles were obtained in 12 cores and red profiles in 6 cores. Soon 77 candidates of high mass protostellar objects (HMPOs) were searched with IRAM and JCMT (Fuller et al. 2005). They identified 22 promising infall candidates. Meanwhile toward 12 UC HII regions, Wyrowski et al (2006) detected 9 blue profiles

with CO (4-3) and ^{13}CO (8-7) lines by APEX. Using MOPRA, Purcell et al. (2006) observed 83 CH_3OH maser-selected regions with lines of CH_3OH (5-4), (6-5), and HCO^+ and H^{13}CO^+ (1-0) transitions. They detected 12 blue profiles. Klaassen & Wilson (2007) observed 23 UC HII regions with outflows using JCMT. They used tracers of HCO^+ (4-3), H^{13}CO^+ (4-3), CO (2-1) and found 9 sources having Infall motion. Toward very early Orion cores which are likely precursors of protostars, Velusamy et al.(2008) detected 27 Orion cores with HCO^+ and H^{13}CO^+ (3-2) by CSO. They found dichotomy in the dynamical status: 9 sources have blue profile and 10 have red profile. These surveys obtained a number of inflow candidates and show inflow motions are common in massive star formation regions.

To further examine characteristics of inflow motions in massive star formation regions, a mapping survey of HCO^+ (1-0), CS(3-2), N_2H^+ (1-0), C^{18}O (1-0) was made with IRAM (Wu et al. 2007). Rotation could be excluded from the spatial distribution of the asymmetric line profiles. Also the peak positions of blue profile and associated molecular outflow can be identified. To see difference of inflow motion at different evolution status, this survey includes two group sources. Group I contains 33 UC HII precursors (PUC HII or HMPOS) and Group II consists of 12 UC HII regions. Using HCO^+ (1-0) nine and seven blue profiles were obtained in Group I and Group II respectively. However there are 4 red profiles in Group I while no red profile in Group II. The asymmetric lines detected result in the blue excess E_{blue} is 0.17 and 0.58 for the two groups respectively, here $E_{\text{blue}} = (N_B - N_R)/N_T$, N_B , N_R and N_T are the number of sources with blue profile, red profile and the sample of the survey (Mardones et al. 1997). Results show the UC HII regions have higher blue excess than their precursors. Meanwhile the results of the survey shows blue profiles are usually peaked at the core center and part of the sources have high velocity outflows. Figure 1 presents the HCO^+ (1-0) mapping grid, comparing of optical thin and thick lines as well as P-V diagrams of two sources, one is a PUC HII and the other is associated with an UC HII region.

We compare the blue excess of the two group sources of this survey with those of previous

surveys. Table 1 gives the blue excess (E) of cores at different evolution statues. We can see the following situations:

(1) For the same HMPOS, With the same tracer HCO^+ (1-0), the E of two surveys are about the same, $\sim 16\%$;

(2) Using different tracers of HCO^+ (1-0) and CO (4-3), $E > 50\%$ was obtained for UC HII regions;

(3) For the youngest massive cores (see Table 1), the E value is negative.

We also compare the E of massive star formation regions with their low mass counterparts. From Table 1, one can see that there is no tendency of E varying with time for the low mass cores. However the tendency that E of the late phase is larger than that of the early phase for massive star formation cores is evident. This contradicts with the theoretical result since radiation pressure of UC HII regions should be larger than that of earlier phases. Possible explanations for the difference may be concerned with thermalization of the flow regions, influence of outflow or turbulence and gas reserves (Wu et al. 2007), which need to be further explored.

3. Probing inflows with high angular resolution observations

To examine inflow motions in the inner regions of massive cores and test the results of the single dish observations, higher angular resolution observations are needed. Especially interferometer is powerful to probe deep layers of cores. Recent years excellent examples such as W51N, NGC 7538 and Sgr B2 were obtained (Zapata et al. 2008; Qin et al. 2008; Qiu et al. 2011). Some other massive core collapse candidates from single dish observations were observed with various interferometers. Below we make a briefly comparison of the line signatures of these cores observed with single dishes and interferometers. Table 2 gives the source name, evolution phase, signatures detected with different resolution observations. The comparing results are as

following:

(1) Generally no obvious conflict was found between the results of single dish and interferometer observations in these cores. And more strong signature of gravitational collapse were detected with interferometers. Core JCMT18354-0649S was mapped with HCN, HCO^+ , H^{13}CO^+ (3-2) and C^{17}O (2-1) at JCMT (Wu et al. 2005). Blue profile was shown in multiple pairs of optical thick and thin lines. Two layer model fitting gave infall velocity of 0.25 km/s. The SMA observations of molecular lines including CH_3OH ($5_{23}-4_{13}$) and HCN (3-2) also showed blue profile which is more prominent than the one obtained by JCMT (Liu et al. 2011a). The infall velocity is 1.3 km s^{-1} from the same model fitting. The inflow signature of W3-SE obtained with IRAM was confirmed by the Combined Array for Research in Millimeter-wave Astronomy (CARMA) (Zhu et al. 2010). For NGC7538, blue profile was observed with single dish, while inverse profile was obtained with SMA (Zhu et al. 2013; Qiu et al. 2011).

(2) Profiles were distinguished in inner regions of the cores. For example, high excitation density molecular lines of CH_3CN (12_4-11_4) and CH_3OH ($8_{-1,8}-7_{0,7}$) detected with the Atacama Large Millimeter/Submillimeter Array (ALMA) in Orion KL region present collapse signature for the first time, which show an inverse P Cygni profile for Source I and blue profile for the hot core (Wu, Liu & Qin 2014). In G9.62-0.19, there are compact cores C, D, E, F and I within a region with a diameter $< 5''$ (Testi et al. 2000). Core E is a young massive star surrounded by a small UC HII region (Hofner 1996), and core F is a very young stellar object (Linz et al. 2005). Hofner et al. (2001) observed G9.62-0.19 with HCO^+ (1-0), SO (43-32) and SiO (5-4) lines using IRAM. The HCO^+ (1-0) line shows both blue and red shifted absorption at a spatial resolution of $27''$. SMA observation revealed that the blue asymmetric profile comes from Core E and the red one from Core F (Liu et al. 2011b). The profile difference of the two cores Source I and the hot core in Orion KL, and core E and core F in G9.62-0.19 is consistent with the results of single dish surveys, $E_{\text{Late}} > E_{\text{Early}}$.

(3) Infall velocity difference at different size of inflow regions was found. For example, in G19.62-0.23, the red shifted gas absorption region of the CN (N=3-2) line is smaller than that of ^{13}CO (3-2), while the infall velocity obtained from CN (3-2) line is larger than that from ^{13}CO (3-2), which is consistent with inside out collapse model (Shu, Adams & Lizano. 1987). G34.26+0.15 is the only source that inverse P Cygni profile was detected in the IRAM survey (Wu et al. 2007). SMA detected six cores in this region. Multiple CN (N=2-1) lines of each core show inverse P Cygni profile (Liu et al. 2013a). The largest infall velocity corresponds to the smallest absorption area. The tendency of the velocity changing with the inflow region size is consistent with the inside-out model too.

(4) Fragmentation was detected. In G10.6-0.4, there are seven sub-millimeter cores. All cores show red shifted absorption gas (Liu et al. 2013b), four of which are associated with infrared point sources. The center core has largest mass and largest infall velocity. The difference of the kinematic and Bondi-Hoyle mass accretion rates is agreed within a factor of 2. These results are consistent with competitive accretion (Bonnell et al. 2001). However, the core structure and mass spectrum need to be further examined.

(5) The SMA observations of G8.68-0.37 did not show infall motion signatures. However, the lines of CO (1-0) and (2-1) observed with PMO and CSO show prominent blue profile. While the HCN(3-2) lines observed with JCMT present red profile although the S/R ratio is low. This source contains an EGO (Ren et al. 2012). Similar situation may be happened in some other EGOs. The survey toward 72 EGO by PMO (Chen et al. 2010) found 29 sources having blue profiles, and 19 have red profiles, giving E of 0.14. In another HCN (3-2) survey of EGOs (Wu, Liu, Reipurth, on going) with JCMT, the blue asymmetric and red asymmetric profiles are 8 and 14 respectively, giving -0.24 of E. In cores like G8.68-0.37, there are inflow motions outside and expanding in the inner, which needs to be studied by more observations. In source G45.12+0.13, NH_3 (4,4) and (5,5) lines detected with 100 m telescope at Effelsberg show inverse P Cygni

Table 1: Blue excesses of inflow surveys

Sources		Evolutionary phases		Ref.
High mass	Earlier than PUC HII	PUC HII	UC HII	
examples		Core JCMT	G 34.26	1,2
E (HCO+(1-0))		17%	58%	3
		15%	70% (CO 4-3)	4,5
HCO+(3-2)	-0.04			,6
Low mass	Class -I	Class 0	Class I	
examples	L1544	B335	L1251B	7,8
E HCN (3-2)	30%	31%	31%	8

Ref.: 1, Liu et al. 2011a; 2. Liu et al. 2013; 3. Wu et al. 2007; 4. Fuller et al. 2005; 5. Wyrowski et al. 2006; 6. Velusamy et al. 2008; 7. Mardones et al. 1997 ; 8. Evans (2003)

profiles (Cesaroni, Walmsley & Churchwell 1992). The VLA observations of NH_3 (2,2) and (4,4) lines with beam size $2''.9 \times 2''.7$ also showed such profiles (Hofner, Peterson, & Cesaroni 1999). However, high spatial resolution observations of $5''$ failed to identify inverse P Cygni profile in this region (Wilner et al. 1996). Such intricate situation in the inner region of a source needs to be explored too.

4. Summary and prospect

Searches for evidence of gravitational collapse of massive star formation cores have been progressed greatly. During the last decade after blue profile found in low mass cores, searches toward various phases of massive dense cores were frequently made. Results suggest that inflow motions are common in massive star formation regions too.

A number of the candidates were observed with high angular resolution and strong evidence

Table 2: A comparison between single dish and interferometer observed results

Source	Phase	Single dish	High resolution	Ref.
JCMT 18354	PUC H _{II}	Blue	Blue	1,2
W3-SE	PUC H _{II}	Blue	Blue	3,4
G9.62-0.19F	Younger PUC H _{II}	Blue or Red?	Red	5,6
Orion KL/Hot	core Younger PUC H _{II}	—	Blue	7
G8.68	PUC H _{II}	Blue-outer; Red-inner?	—	8
G19.61-0.23	UC H _{II}	Blue or Red?	Inverse P Cygni	3,9
G9.62+0.19E	UC H _{II}	Blue or Red?	Blue	5,6
NGC7438 IRS1	UC H _{II}	Blue	Inverse P Cygni	3, 10
G10.6-0.4	UC H _{II}	Blue	Inverse P Cygni	11,12
G34.26-0.15	UC H _{II}	Inverse P Cygni	Inverse P Cygni	3, 13
Orion KL/Source I	Radio source	—	Inverse P Cygni	7
G45.12+0.13	UC H _{II}	Inverse P Cygni	Inverse P Cygni	14, 15
			No inverse PCygni	16

Ref.: 1. Wu et al. 2005; 2. Liu et al. 2011; 3. Wu et al. 2007; 4. Zhu et al. 2010; 5. Hofner et al. 2001; 6. Liu et al. 2011; 7. Wu et al. 2014; 8. Ren et al. 2012; 9. Wu et al. 2009; 10. Zhu et al. 2013; 11. Wu & Evans, 2003; 12. Liu et al. 2013a; 13. Liu et al. 2013b

of inverse P Cygni was found. Velocity changes at different sizes of inflow regions were detected. Multiple cores and their inflow motions were also obtained. These results suggest that high mass stars may form via accretion model.

There may be foundational difference between collapse of the two kinds of star formation processes. Surveys in massive cores at different evolutionary statuses show that there is evolution tendency of the blue excess. And profiles of core pairs which is consisted of a young massive core and a UC H_{II} region are consistent with $E_{Late} > E_{Early}$. Inflow motion appears to occur at outer side while expanding or outflow occur inside of some massive cores, which is not seen in low mass

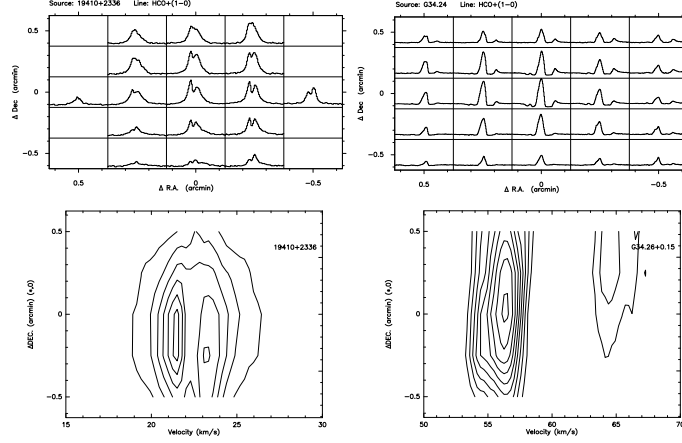


Fig. 1.— Left: UC HII precursor 19410+2336; Right: UC HII region G34.26+0.15. (See Table 1 of Wu et al. 2007. The figures are not published yet.)

cores so far. Structure, mass distribution and inflow processes of massive dense cores need more probing. ALMA has better sensitivity and resolution, which will enable us detect fragmentation or mass secretion, and determine their mass spectra. Future studies will provides us better pictures of gravitational collapse in massive star formation regions.

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REFERENCES

- Bonnell, Ian A.; Bate, Matthew R.; Zinnecker, Hans; 1998, MNRAS, 298, 93
- Bonnell, I. A.; Clarke, C. J.; Bate, M. R.; Pringle, J. E. 2001, MNRAS.,324, 573
- Cesaroni, R.; Walmsley, C. M.; Churchwell, E. 1992, A&A, 256, 618
- Chen, Xi; Shen, Zhi-Qiang; Li, Jing-Jing; Xu, Ye; He, Jin-Hua, 2010, ApJ, 710, 150
- Fuller, G. A.; Williams, S. J.; Sridharan, T. K. 2005; A&A, 4442, 949
- Hofner, P.; Kurtz, S.; Churchwell, E.; Walmsley, C. M.; Cesaroni, R. 1996, ApJ, 460, 359
- Hofner, P., Peterson, S., & Cesaroni, R. 1999, ApJ, 514, 899
- Hofner, Peter; Wiesenmeyer, Helmut; Henning, Thomas, 2001, ApJ, 549, 425
- Jijina, Jasmin; Adams, Fred C. 1996, ApJ, 462, 874
- Klaassen, P. D.; Wilson, C. D. 2007, ApJ, 663, 1092
- Klaassen, P. D.; Testi, L.; Beuther, H. 2012, A&A, 538,140
- Liu, Tie; Wu, Yuefang; Liu, Sheng-Yuan; Qin, Sheng-Li; Su, Yu-Nung, 2011b, ApJ, 730, 102
- Liu, Tie; Wu, Yuefang; Zhang, Huawei, 2013a, ApJ, 776, 29
- Liu, Tie; Wu, Yuefang; Wu, Jingwen; Qin, Sheng-Li; Zhang, Huawei, 2013b , MNRAS, 436,
1335
- Liu, Tie; Wu, Yuefang; Zhang, Qizhou; Ren, Zhiyuan; Guan, Xin; Zhu, Ming, 2011a, ApJ, 728,
91
- Mardones, D.; Myers, P. C.; Tafalla, M.; Wilner, D. J.; Bachiller, R.; Garay, G. 1997, ApJ, 489,
719

- Purcell, C. R.; Balasubramanyam, R.; Burton, M. G.; Walsh, A. J.; Minier, V.; et al. 2006, MNRAS, 367, 553
- Qin, Sheng-Li; Zhao, Jun-Hui; Moran, James M.; Marrone, Daniel P.; Patel, Nimesh A .; Wang, Jun-Jie; Liu, Sheng-Yuan; Kuan, Yi-Jehng 2008, ApJ, 677, 353
- Qiu, Keping; Zhang, Qizhou; Menten, Karl M. 2008, ApJ, 728, 6
- Ren, Zhiyuan; Wu, Yuefang; Zhu, Ming; Liu, Tie; Peng, Ruisheng ; Qin, Shengli; Li, Lixin 2012, MNRAS, 422, 1098
- Shu, Frank H.; Adams, Fred C.; Lizano, Susana, 1987, ARA&A, 25, 23
- Testi, L.; Hofner, P.; Kurtz, S.; Rupen, M. 2000, A&A, 359, L5
- Velusamy, T.; Peng, R.; Li, D.; Goldsmith, P. F.; Langer, William D. 2008, ApJ, 688, L87
- Wilner, D. J., Ho, P. T. P., & Zhang, Q. 1996, ApJ, 462, 339
- Wolfire, Mark G.; Cassinelli, Joseph P. 1987, ApJ, 319, 850
- Wu, Jingwen; Evans, Neal J., II 2003, ApJ, 592, L79
- Wu, Yuefang; Liu, Tie; Qin, Shengli 2014, ApJ, 791, 123
- Wu, Yuefang; Henkel, Christian; Xue, Rui; Guan, Xin; Miller, Martin, 2007, ApJ, L37
- Wu, Yuefang; Zhu, Ming; Wei, Yue; Xu, Dandan; Zhang, Qizhou et al., 2005, ApJ, 628, L57
- Wyrowski, F.; Heyminck, S.; Gusten, R.; Menten, K. M. 2006, A&A, 454, L95
- Yorke, Harold W.; Sonnhalter, Cordula 2002, ApJ, 569, 846
- Zapata, L. A.; Palau, A.; Ho, P. T. P.; Schilke, P.; Garrod, R. T.; Rodriguez, L. F.; Menten, K. 2008, A&A, 479, L25

Zhou, Shudong; Evans, Neal J., II; Koempe, Carsten; Walmsley, C. M. 1993, ApJ, 404, 232

Zhu, Lei; Wright, M. C. H.; Zhao, Jun-Hui; Wu, Yuefang, 2010, ApJ, 712, 674

Zhu, Lei; Zhao, Jun-Hui; Wright, M. C. H.; Sandell, Goran; Shi, Hui; Wu, Yue-Fang; Brogan, Crystal; Corder, Stuartt 2013, ApJ, 779, 51